Printable Spacecraft:
Flexible Electronic Platforms for NASA Missions

NIAC Program Spring Symposium

Ms. Kendra Short
Dr. David Van Buren

Acknowledgements to our JPL team:
Mike Burger, Peter Dillon, Brian Trease, Shannon Statham

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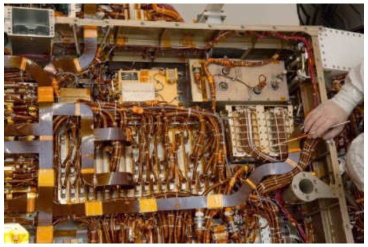
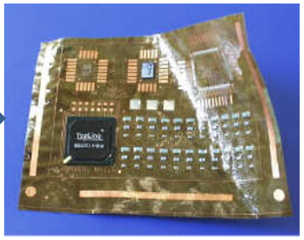
Topics

- Introduction – What is a Printable Spacecraft?
- Proposal Objectives – Conclusions and Findings
  - #1: Is it a Viable Concept?
  - #2: Survey of Capabilities
  - #3: Identifying Gaps
  - #4: Investment Roadmap
- Summary

The Basic Idea…

- Flexible printed electronics have revolutionized consumer products such as cellular phones and PDAs, allowing greater functionality with decreasing size and weight. We think the same can be done for spacecraft.

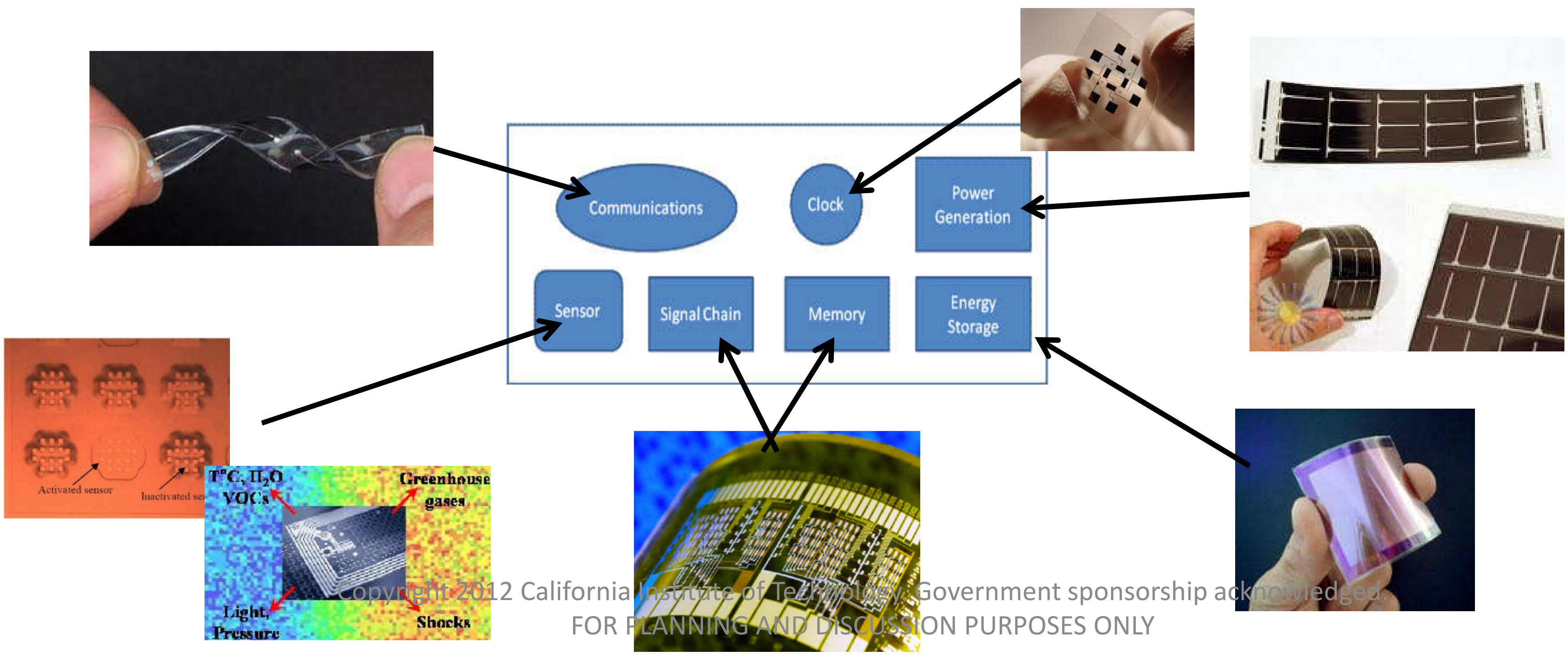




- We propose to investigate the feasibility of implementing a complete end to end spacecraft - science measurement through data downlink – based purely on flexible substrate "printed" electronics.
- The benefits would be decreased design/fabrication cycle time, reduced unit level mass and volume, and decreased unit level cost.

The Key Technology…

- The printing process has been adapted to work with flexible mechanical substrates and specialized inks with specific conductive, insulating, photovoltaic, mechanical, and chemical properties to print just about every subsystem you would need for an entire spacecraft.

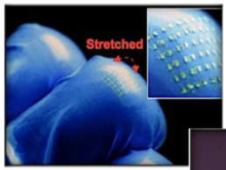


Flexible Printed Electronics 101

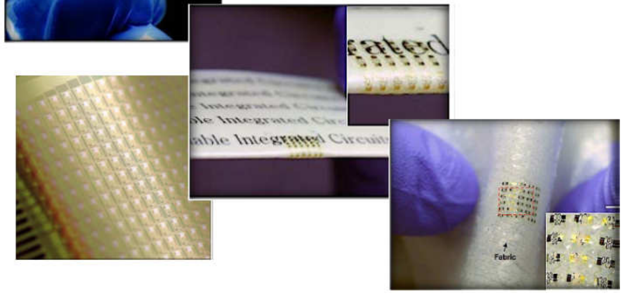
Substrates

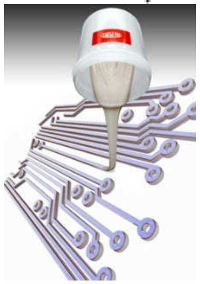
Flexible, stretchable, dissolvable

Polyimide	Silicon	Kapton
Metallic sheet	Polymers	Ceramics
Plastics	Glass	Paper



mc10
High Performance Conformal Electronics





Inks

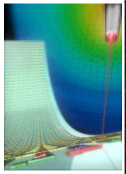
Aqueous, catalyst, CNT infused, etched

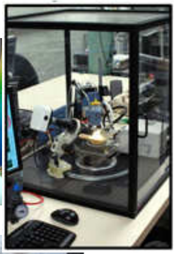
Ferrites	Conductors	Metals
Polymers	Insulators	Biological

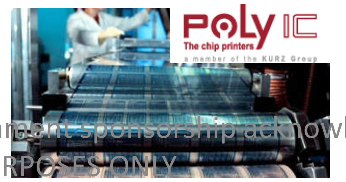
Manufacturing

High precision, sheet based, production

E-jet	Roll to Roll	Gravure
Aerosol-jet	Ink-jet	Flexo
Screen printing	Transfer	







Printable Spacecraft: Flexible Electronic Platforms for NASA Missions

Principal Investigators: Ms. Kendra Short, Dr. David Van Buren
Jet Propulsion Laboratory, California Institute of Technology

1.1.1 Objectives

Our objective is to explore the revolutionary architectural concept of designing and fabricating a spacecraft based entirely on flexible substrate printed electronics. We see opportunities to leverage the current commercial consumer electronics industry investment by augmenting its capabilities with advanced materials and engineering research performed by universities, industry, and NASA centers. With this revolutionary capability, NASA would be able to dramatically improve performance, flexibility, weight, cost, schedule, reliability and operational simplicity for many scientific and human exploration missions.

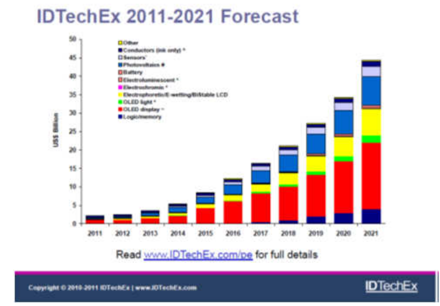
We propose to:

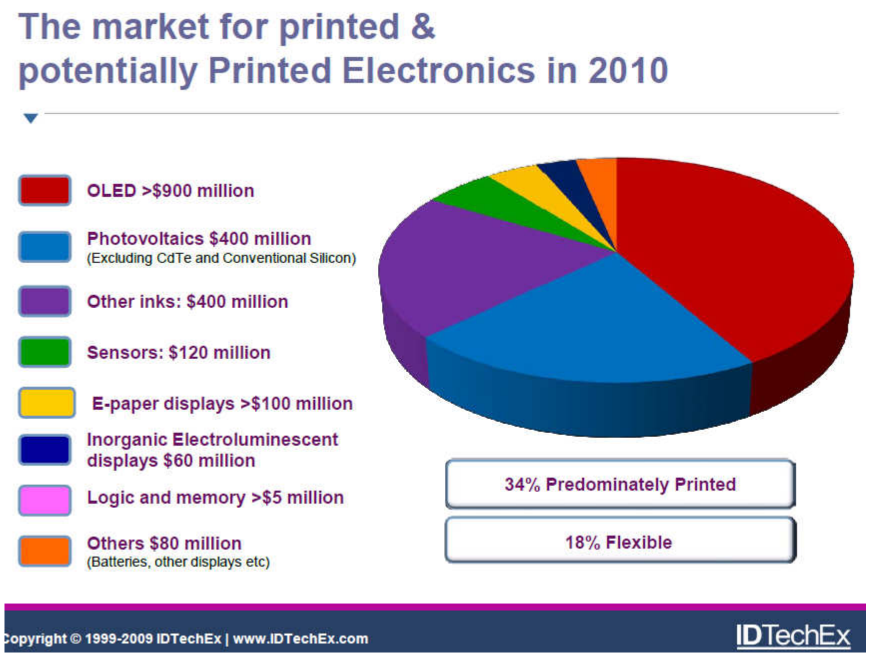
1. Explore the viability of printed technologies for creating small 2D spacecraft, including mission concepts, architectures, materials, subsystems, integration and manufacturing aspects.
2. Complete an inventory of the availability and capability of relevant sensors and spacecraft subsystem elements.
3. Identify gaps between what is currently available in industry products and what is required for space applications.
4. Develop a high-level strategy for technology investments needed to fill those gaps.

Objective #1: Is it a Viable Concept?

- Conclusion: Yes it's a viable concept

- Findings:
  – Sufficient market growth and commercial investment for this technology.
    - Projections show market growth.
    - Industry alliances and government support for technology is strong
    - Sufficient breadth of companies and Universities
  – Sufficient coverage across "spacecraft subsystems" and investments in manufacturing techniques and fundamentals building blocks (inks, materials, design rules)
  – Sufficient science mission applications which show benefit due to benefits of low recurring cost, large numbers, and low mass.
  – Sufficient engineering applications which show benefit due to flexibility and form factors

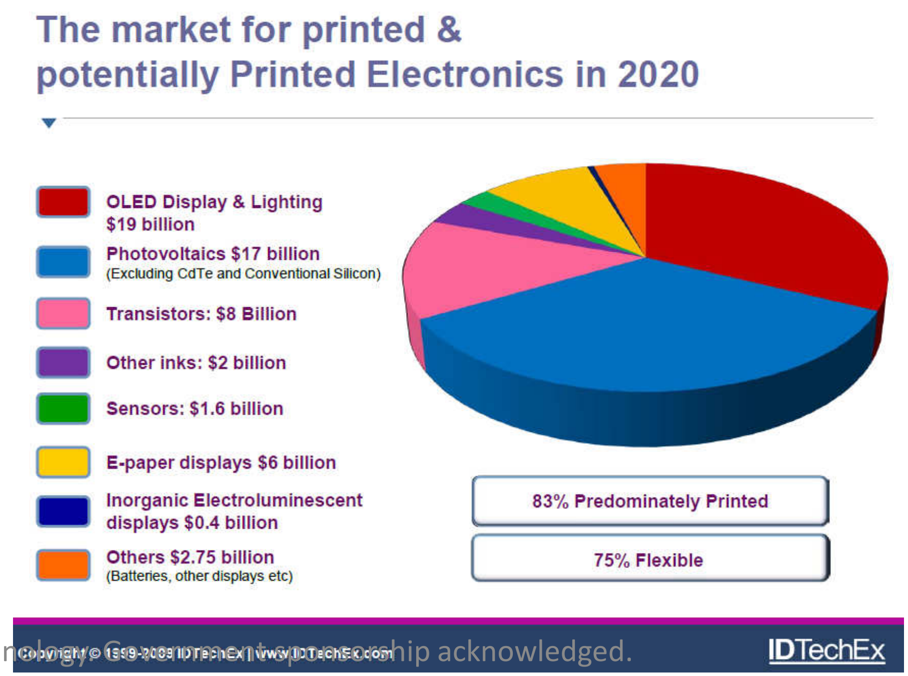




Total market (today) > $2B

Total market (projected 2020) > $58B

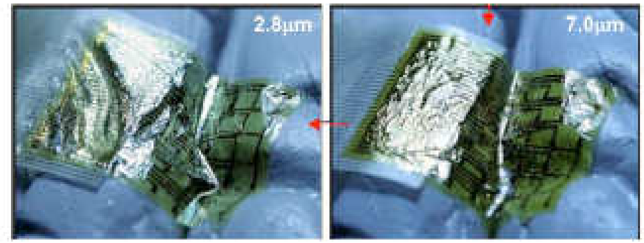
NASA can not make this kind of investment and must leverage the developments in the commercial sector

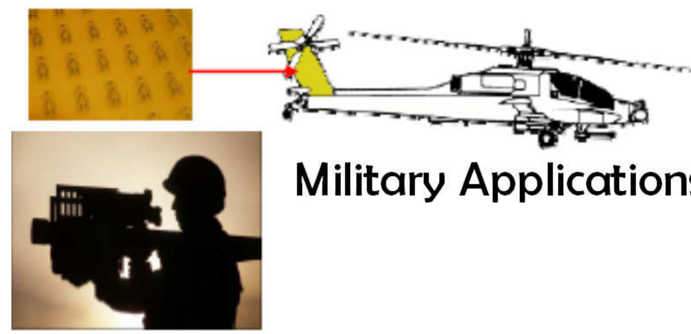


Where is the Industry Focused….

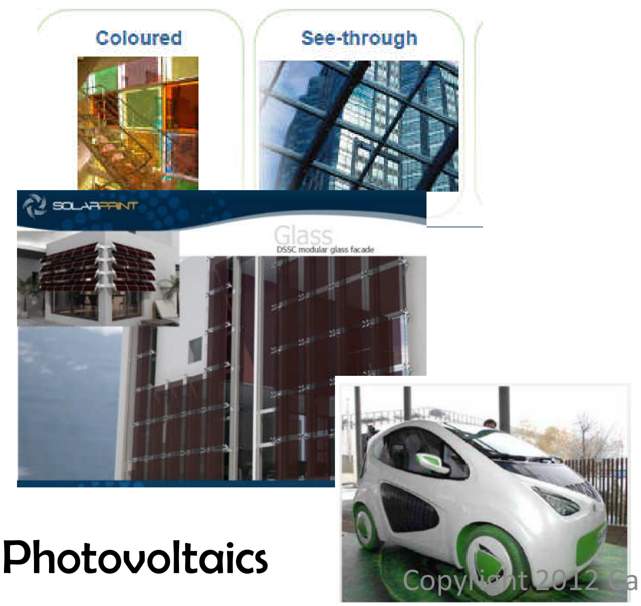
Interactive screens and displays

Bio-medical





Military Applications

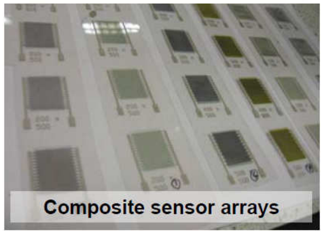


Photovoltaics

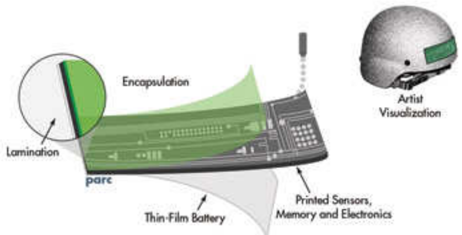
Innovative consumer products, multi-function textiles

RFID, inventory, smart packaging

POLYID®
Printed RFID

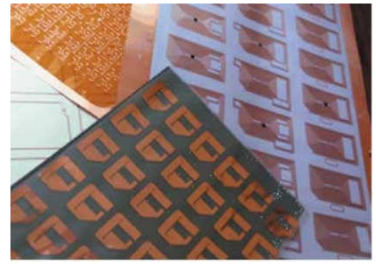


Ink-jet printed gas sensor array using polymer functionalization

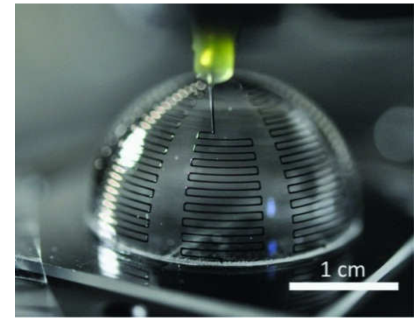


Blast dosimeters, printed with electronic sensors, memory processors and thin-film batteries. (made for DoD by PARC)

SENSORS

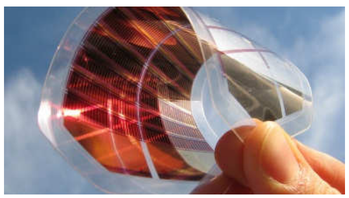


Typical flexible printed antenna



UofI researchers develop nanoparticle inks to print 3D antennas

ANTENNAS

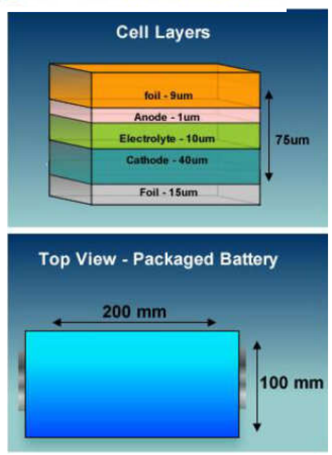


Flexible Organic Photovoltaic cell (Source: Fraunhofer ISE)

Slot-die coating of Plexcore™ photo-voltaic ink system on a 500mm R2R line

PHOTOVOLTAIC

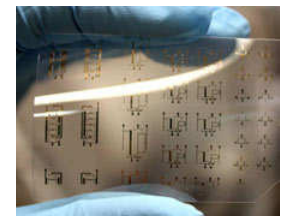
The printed, flexible and ecologicalSoftBattery®

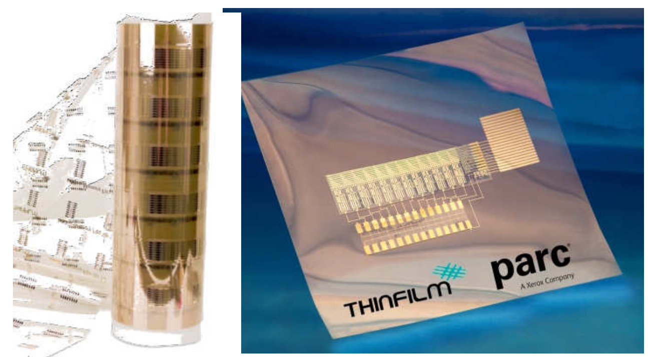


Thick film R2R deposition of solid state battery

BATTERY

These flexible carbon nanotube integrated circuits are the fastest low-power transistor arrays ever fabricated using a printer.





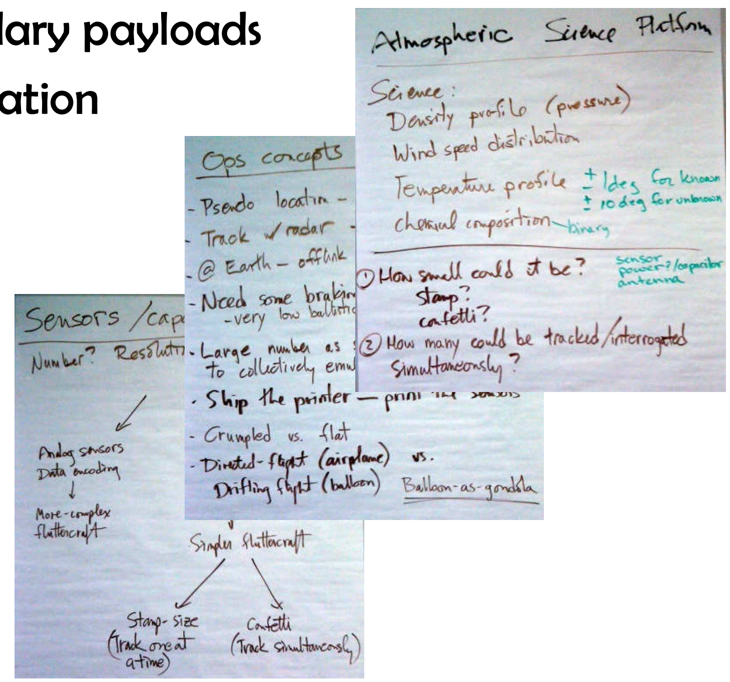
The world's first printed non-volatile memory device addressed with complementary organic circuits, the organic equivalent of CMOS circuitry

MEMORY/LOGIC

Science Mission Applications

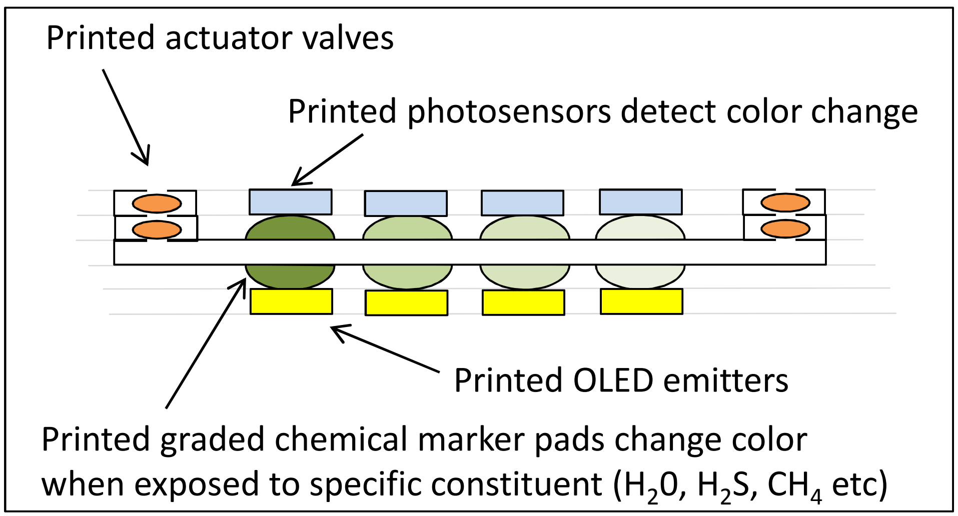
- Held a half-day workshop to explore science mission applications and architectures.
- Goal: Sketch a science mission and architecture which exploit the characteristics of a printed spacecraft
  - <u>Flexibility</u>: Storage and deployment options, Change shape on orbit, on surface, Conformal on other surfaces
  - <u>Low recurring costs</u>: Large numbers, “Disposable” for hi-risk environments
  - <u>Low Mass & Volume</u>: Large numbers, Secondary payloads
  - <u>Short Cycle Time</u>: Iterative testing and evaluation
- Participants from JPL & Xerox PARC
  - Scientists & Mission designers
  - Printable practitioners & Technologists

Science	Instruments	Mission Concepts	NIAC Team	Special Guests
Julie Castillo-Rogez	Allen Farrington	Brent Sherwood	Kendra Short	Andrew Shapiro
Nathaniel Livesey	Cindy Kahn	John Crawford	Dave Van Buren	Leah Lavery
Joel Hurowitz	Rob Staehle	Jeff Booth	Peter Dillon	Greg Whiting
Peter Willis	Neil Murphy	John Elliot	Mike Burger	
Sabrina Feldman	Al Nash	Andy Klesh	Shannon Statham	
	Paula Grunthaner		Brian Trease	

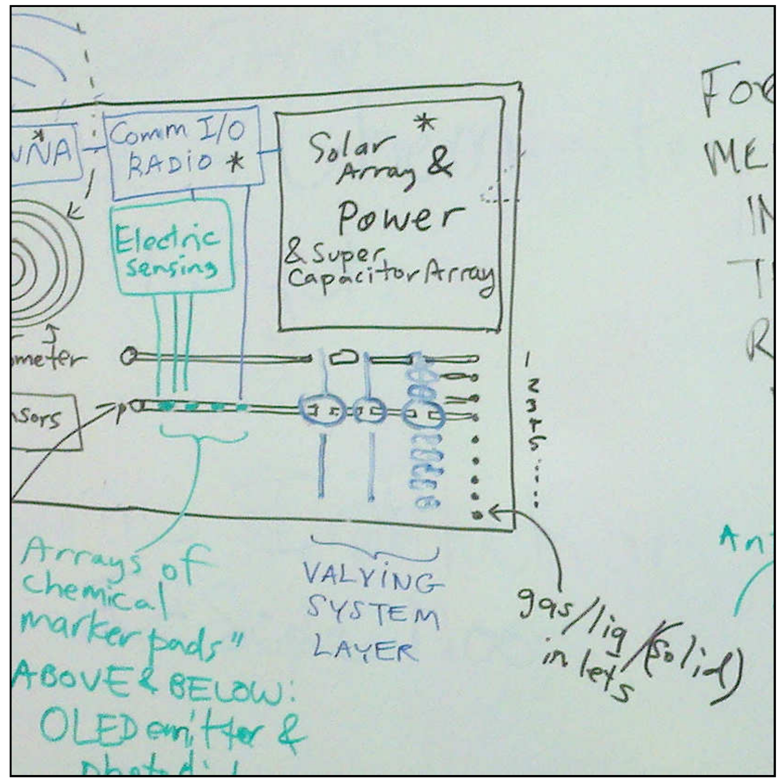


Proposed Mission Science

- Focus on exploration rather than hypothesis testing
- Detection rather than measurement: “I detect X!”
- In-situ chemical, pressure, temperature sensing regarded as early high-payoff area
  - Atmospheres - flutterflyers
  - Surfaces - flutterlanders



Concept for printed threshold chemical sensor for Mars soil volatiles or Titan lakeshore organics

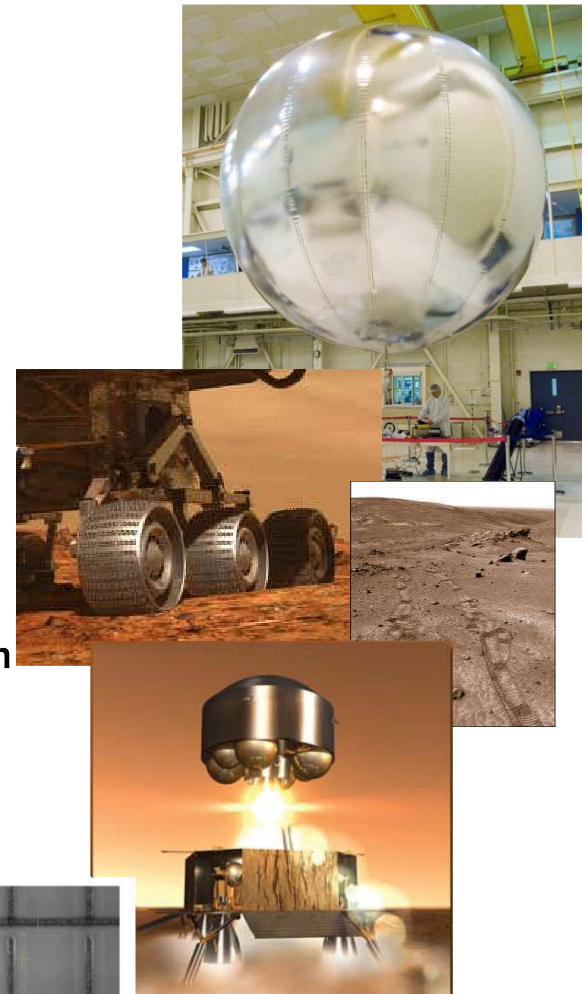


Proposed Mission Architectures

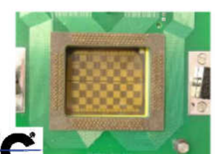
- Both teams focus on network based missions (atm, surface)
- Emplace with traditional carrier spacecraft using flutterflyer / flutterlander concept
- Atmospheric sensors designed to stay aloft for long periods
- Large number of diverse threshold sensors can emulate a complex measurement
- Very small radiated data packet – just enough to encode "I detect X!"
- Sense telemetry with traditional orbital asset
- Form factors range from sheet to postage stamp to confetti

Proposed Engineering Applications

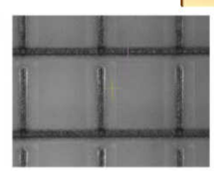
- Next is an Engineering Workshop (April)
  - Further define functional requirements of one of the network mission platforms
  - Explore other engineering applications.
    - Conforms to interior of sample return capsule recording environmental history of sample (pressure, temp, atm constituents)
    - Conforms to rover wheel performing engineering mechanics of traverse or surface science measurements throughout terrain.
    - Functional systems and sensors imprinted onto balloon material substrate or solar sail and eliminate the gondola or spacecraft.
    - Mass/volume/cost savings in electronics packaging



OPTOMEC® Additive Manufacturing Systems — from Nano to MACRO™



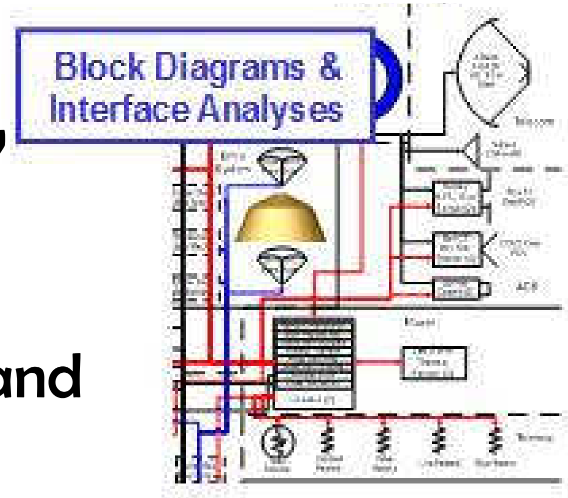
Polymer TFT Display



Ag Gates & Interconnects

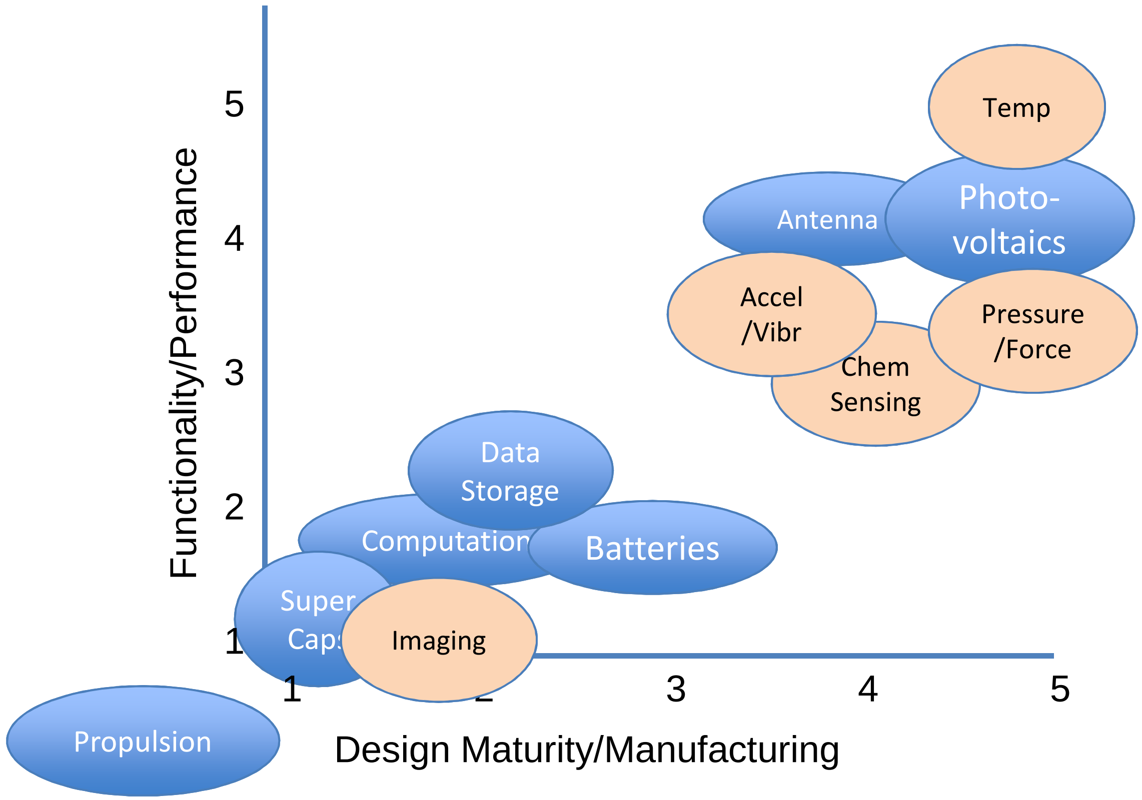
Objective #2: Inventory of sensors and subsystem elements.

- Conclusion: Variability in functionality and maturity
- Findings:
  - Huge variability in maturity of design and manufacturing approaches
  - Functionality is limited in many areas
  - Even for mature components, there may be a hit on key figures of merit.
  - There are opportunities for hybrid systems, depending on which characteristics of a printed system are to be optimized for the application (flexibility, printability, cost, mass).



Avionics	
	data storage
	processing
	logic
	clock
	data modulation/encryption
Power	
	photovoltaics
	batteries
	supercapacitors
	power management
Thermal	
	temperature control
Communciations	
	antennae
	transmitter
	receiver

Capability Map of Subsystems/Sensors



	Design Maturity/Manufacturing
1	Demonstrated in lab/university environment
2	Demonstrated by commercial company
3	First generation product
4	Second generation product/optimized for manufacturing
5	Third generation product/mass production.

	Functionality / Performance
1	Basic functionality demonstrated but too low for practical use
2	Functionality supportive of rudimentary systems
3	Acceptable performance but less than that of non-printed counterparts.
4	Similar performance but with notable drawbacks
5	Performance equivalent to non-printed counterparts

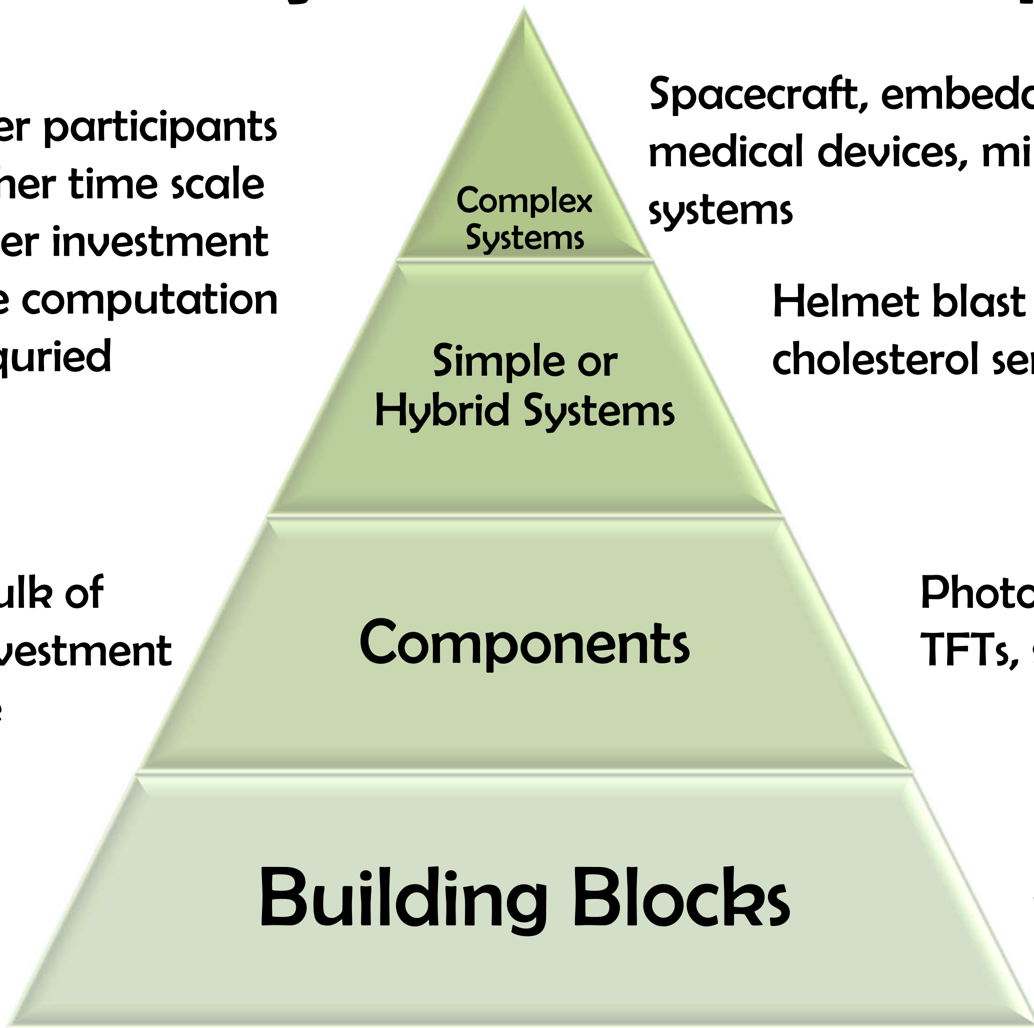
Objective #3: Identify gaps between availability and need

- Conclusion: Gaps exist in key areas, but can be closed multiple ways.
- Findings:
  - Clearly there are gaps between performance and need in some key functional areas – but how do you define the need with such a variety of applications?
  - "Disruptive thinking" is needed to redesign mission architectures compatible with the existing capabilities
  - Industry will continue to invest and close the gap in most areas
  - The key areas which NASA will need to examine are:
    - System Design (NASA)
    - Sensors development – sensitivity and variety (NASA)
    - Environmental characterization (NASA)
    - Computational, data functionality (partnership)

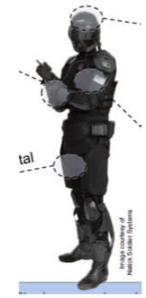
Pyramid of Complexity

Fewer participants
Further time scale
Larger investment
More computation requried

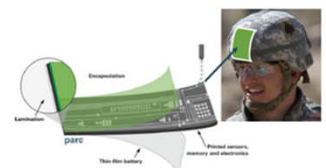
The bulk of the investment is here



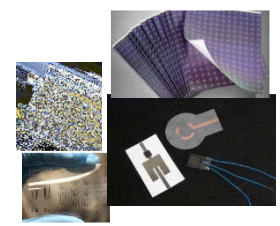
Spacecraft, embedded medical devices, military systems



Helmet blast dosimeter, cholesterol sensor, displays

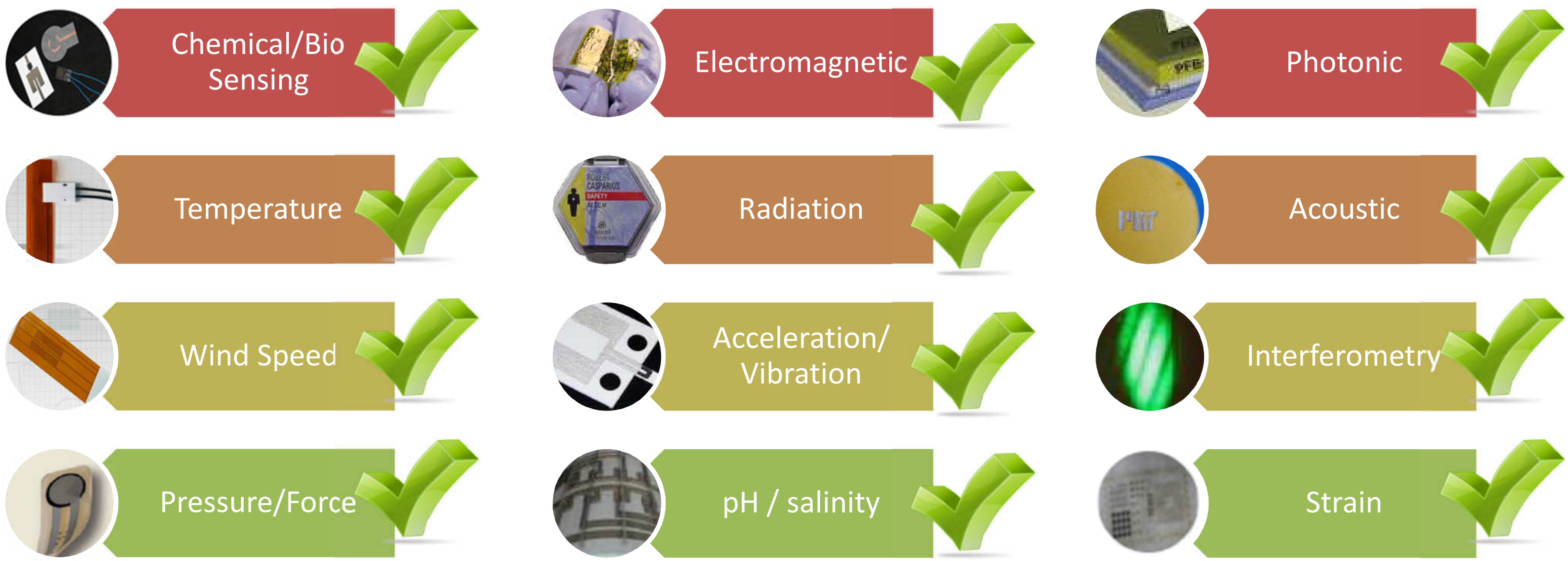


Photovoltaics, antennas, TFTs, sensors, batteries



inks, substrates, materials, manufacturing, design rules

Sensor types and capabilities



What’s needed?

- nanoMolar chemical
- High resolution time
- Single photon
- R>100 Spectroscopy

Objective #4: Technology investment strategy

System technologies

- Integrated System Design
- Hybridizing
- Smart Networks
- Mobility
- Multiplexed Communication
- Tracking
- Deployment/Support systems

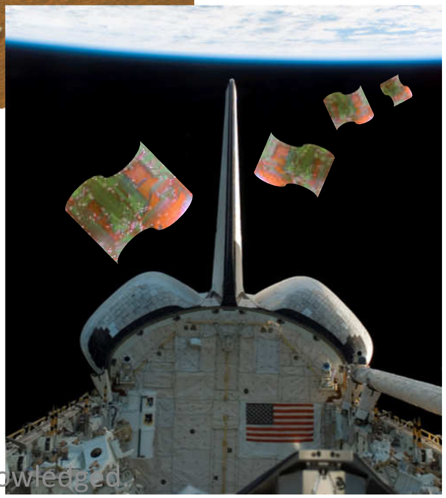
Subsystems/Sensors

- Data Storage
- Computation/Processing
- Propulsion
- Imaging
- Spectroscopy

Environments

- Radiation
- Temperature ranges
- Thermal cycling
- Micrometeoroid
- Planetary protection sterilization
- Outgassing
- Lifetime, Storage
- Atmospheric constituents

Summary



- We still think this crazy idea holds together.
- There's a lot of energy around thinking differently about missions and spacecraft.
- There's a lot of energy around pushing the application of this technology.
- Even if we don't get to the point of a highly functional, flexible, completely printed spacecraft, we will have learned a lot along the way that can benefit our traditional platforms.